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A one-billion-year-old Scottish meteorite impact

C.L. Kirkland[1,*], T.M. Erickson[1,2], T.E. Johnson[1], T. Prave[3,4], R.A. Strachan[5], M.L. Daggitt[1,§], M.I.H. Hartnady[1], S.M. Reddy[1], R.J.M. Taylor[6], B.V. Ribeiro[1], K. Rankenburg[7], U. Kirscher[1], and S. Fischer[3]

[1]Timescales of Mineral Systems Group, School of Earth and Planetary Sciences, Curtin University, Perth, WA 6102, Australia
[2]Amentum–JETS II, Astromaterials Research and Exploration Science (ARES) Division, NASA Johnson Space Center, Houston, Texas 77058, USA
[3]School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9TS, UK
[4]Department of Geology, University of Tartu, 50411 Tartu, Estonia
[5]School of the Environment and Life Sciences, University of Portsmouth, Portsmouth BS1 6NB, UK
[6]Carl Zeiss Microscopy Ltd., Cambourne, Cambridgeshire CB23 6DW, UK
[7]John de Laeter Centre, School of Earth and Planetary Sciences, Curtin University, Perth, WA, 6102 Australia

ABSTRACT

The Stoer Group in northwest Scotland is one of the oldest well-preserved sedimentary successions in Europe and includes the Stac Fada Member, an impact ejecta deposit. Here we report U-Pb analyses on shocked zircon grains that yield an age of 990 ± 22 Ma, consistent with an early Tonian Pb-loss event that affected the Stac Fada Member but not its bounding strata. We interpret these data to record the timing of impact, which occurred some 200 m.y. after the previously determined 1177 Ma alkali feldspar $^{40}Ar/^{39}Ar$ age. The alkali feldspar we find within the Stac Fada Member yields Rb-Sr ages of ca. 1735 Ma and 1675 Ma, consistent with a detrital provenance from Paleoproterozoic granites. Our new age constrains the Stoer Group to the early Tonian and suggests a new Neoproterozoic plate tectonic context for these rocks. These data revise the age of some of the oldest known nonmarine microfossils in the UK and their role for timing the eukaryotic colonization of land.

INTRODUCTION

Although impact cratering has been a major factor in shaping planetary bodies and their satellites, evidence for meteorite impacts on Earth is relatively rare and fragmentary due to the efficiency of plate tectonics and erosion in remaking land surfaces. Compounding that aspect is the difficulty in dating impact deposits; ~80% of hypervelocity impact structures currently lack precise ages (Osinski et al., 2022). In part, this difficulty is a function of the scarcity of geochronometers amenable to isotopic resetting by shock deformation and related thermal overprinting but that are robust enough to survive geologic time. Zircon ($ZrSiO_4$) is one mineral that is sufficiently physically and chemically robust to survive impacts and may retain diagnostic impact-related microstructures, including lamellae of its high-pressure polymorph reidite. Reidite requires shock pressures >20 GPa and is found in various impact-related rock types (Reddy et al., 2015) including impact melt–bearing breccias (Erickson et al., 2017) and shocked basement rocks in the central uplift of impact structures (Cox et al., 2018). The U-Pb systematics of granular zircon, which can form by postimpact recrystallization of reidite-bearing zircon, can constrain the age of impacts (e.g., Cavosie et al., 2015; Kenny et al., 2017).

Here, we report U-Pb isotopic analyses of shocked zircon recovered from the Stac Fada impact deposit in NW Scotland (Amor et al., 2008; Kenny et al., 2019; Osinski et al., 2021; Parnell et al., 2011; Reddy et al., 2015; Simms, 2015) that yield an age of 990 ± 22 Ma. Our revised age for the impact is 200 m.y. younger than a previously determined $^{40}Ar/^{39}Ar$ alkali feldspar age of 1177 ± 5 Ma (Parnell et al., 2011), necessitating rethinking of long-held concepts about the Stenian to early Tonian plate tectonic evolution of eastern Laurentia and the age of one of the oldest known assemblages of nonmarine eukaryotes (Strother et al., 2011).

THE STAC FADA IMPACT

The Stac Fada Member is part of the Stoer Group in NW Scotland (Fig. 1). The group is traditionally placed as Stenian (1200–1000 Ma) in age, making it the oldest sedimentary succession in Britain and one of the oldest nonmetamorphosed lithological sequences in Europe (Goodwin et al., 2024). It is a siliciclastic-dominated largely nonmarine succession, as much as 2.5 km thick, that rests unconformably on Archean basement rocks of the Lewisian Gneiss Complex and is itself cut by an angular unconformity at the base of the overlying fluviatile sandstones of the Tonian Torridon Group (Rainbird et al., 2001; Stewart, 2002). Locally, the Stoer Group contains eukaryotic microfossils that have been central to ideas about the colonization of land surfaces in the late Precambrian (Strother et al., 2011). The group is conventionally thought of as having been deposited in a rift basin (Stewart, 2002), but new age constraints imply that the crustal-scale Outer Hebrides fault (Fig. 1A) originated as a thrust temporally equivalent to the late Stenian–early Tonian Grenville orogeny and that the Stoer Group may have accumulated in a thrust-top basin (Metcalfe et al., 2024).

The Stac Fada Member crops out for some 60 km southwest from the village of Stoer southwest along the coast to Poolewe (Fig. 1B) and was originally interpreted as a volcaniclastic deposit (Stewart, 2002). However, discovery of planar deformation features in quartz and elevated platinum-group element concentrations (Amor et al., 2008) as well as reidite lamellae in zircon (Reddy et al., 2015) led to its reinterpretation as an impact ejecta blanket (Amor et al., 2008; Branney and Brown, 2011) or phreatomagmatic impact

C.L. Kirkland https://orcid.org/0000-0003-3367-8961
*c.kirkland@curtin.edu.au
§Currently at School of Physics, Maths and Computing, Computer Science and Software Engineering, The University of Western Australia, Perth, WA6009, Australia

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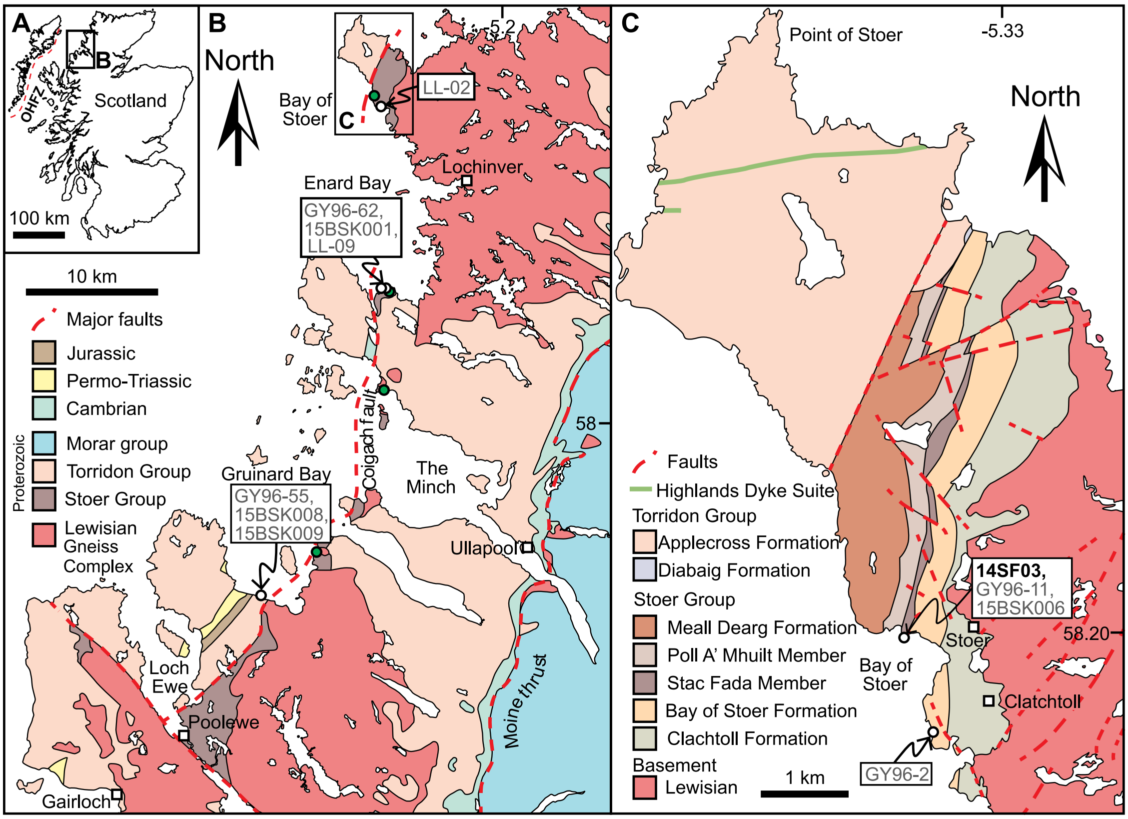

Figure 1. (A) Location of study area in NW Scotland and position of Outer Hebrides thrust fault (OHFZ). (B) Geological map of NW Scotland showing Stoer Group and location of geochronology sample locations. (C) Geologic map at Bay of Stoer showing location of Stac Fada Member sample 14SF03 used in this study. Latitude and longitude are given in decimal degrees (WGS84). Samples GY96-2, GY96-11, GY96-55, and GY96-62 (Rainbird et al., 2001), samples 15BSK001, 15BSK006, 15BSK008, and 15BSK009 (Kenny et al., 2019), and samples LL-02 and LL-09 (Lebeau et al., 2020) are also denoted as white circles. Ar-Ar samples reported by Parnell et al. (2011) are denoted as green circles.

deposit (Osinski et al., 2021). The unit is between 2 and 12 m thick (Lawson, 1973) and is characterized by a matrix-supported breccia with clasts ranging in shape from rounded to angular and in size from centimeters to several meters. Clasts consist of material derived from the underlying Stoer Group sandstones and Lewisian gneiss. Three features are noteworthy. Firstly, the topmost layers of the Stac Fada Member contain varying concentrations of ejecta spherules several millimeters to a few centimeters in size. Secondly, chloritized shards of former impact melt are distributed throughout the matrix. Thirdly, patches of honeycomb-like networks of feldspar are interpreted as postimpact degassing structures. One of the unusual aspects of the Stac Fada Member is that, unlike most impact deposits that consist of primary ejecta, it is formed almost entirely of reworked and resedimented material (Osinski et al., 2021). The site of the source impact structure is debated (Amor et al., 2019; Simms, 2015).

DETRITAL ZIRCON WITHIN THE STAC FADA MEMBER

The analyzed sample of the Stac Fada Member (Fig. 1B) was collected from the type locality on the northern side of the Bay of Stoer (58.2014°N, 5.3482°W; Fig. 1C). It is a poorly sorted matrix-supported breccia with centimeter-size lithic clasts, dust pellets, accretionary lapilli, and devitrified impact glass (Fig. S1 in the Supplemental Material[1]). Zircon grains were separated, mounted, imaged, and analyzed following the techniques detailed in the Supplemental Material. Five grains were identified as shocked zircon, being marked by both planar deformation features and amorphous domains and exhibiting granular textures (neoblasts) with a systematic misorientation relationship (90°/<110>) between the granules and host zircon (Figs. 2A–2C; Figs. S2–S6). These features are consistent with recrystallization during postshock heating to temperatures of ~1200 °C (Kusaba et al., 1985), with one grain (E/178) showing complete recrystallization (Fig. 2C; Fig. S6). Electron backscatter diffraction reveals systematic alignment of *c*-axes and <110> in the granular zircon domains as evidence for the former presence of reidite (Cavosie et al., 2018). Two of the five granular zircon grains still preserve reidite, one with <1% by area of thin reidite lamellae (Fig. 2A; Fig. S5) and another with >60% composed of interlocking reidite (Fig. 2B; Fig. S2), the latter among the highest proportions known. The latter grain also has granular zircon neoblasts misoriented 90°/<110> from the host that occur as a thin rind along its exterior and within fractures.

[1]Supplemental Material. Detailed methodologies, supplementary images, and isotopic datasets. Please visit https://doi.org/10.1130/GEOL.S.28762277 to access the supplemental material; contact editing@geosociety.org with any questions.

GEOCHRONOLOGY

Forty sensitive high-resolution ion microprobe (SHRIMP) U-Pb analyses were collected from the five shocked zircon grains and their granular neoblasts (Figs. 2A–2C), and a further 38 analyses were collected from 21 zircon grains from the same sample that lack evidence of shock metamorphism. Thirty-six analyses of the shocked grains were variably discordant and, along with 21 zircon grains lacking shock features, yield $^{238}U/^{206}Pb$ ages (2σ) ranging from ca. 2700 to 800 Ma (Fig. 2D). This age distribution is consistent with isotopic disturbance and Pb loss during the Proterozoic and Phanerozoic. The remaining 17 nonshocked zircons have concordant ages consistent with their derivation from the Neoarchean to Paleoproterozoic Lewisian Gneiss Complex. Amorphous zircon grains are susceptible to resetting by fluids (Geisler et al., 2003), consistent with their comparatively young ages (<900 Ma).

Three concordant analyses of granular zircon neoblasts yield an age of 990 ± 22 Ma (mean square of weighted deviates [MSWD] = 1.7; $p = 0.14$; Fig. 2D), interpreted as the best estimate of impact-related shocked zircon formation. This age is supported by three analyses on a single zircon grain that yield a lower intercept on concordia of 945 ± 57 Ma, with an upper intercept of ca. 2565 Ma (MSWD = 1.19). This grain is interpreted as an Archean zircon crystal that experienced radiogenic Pb loss during the Proterozoic.

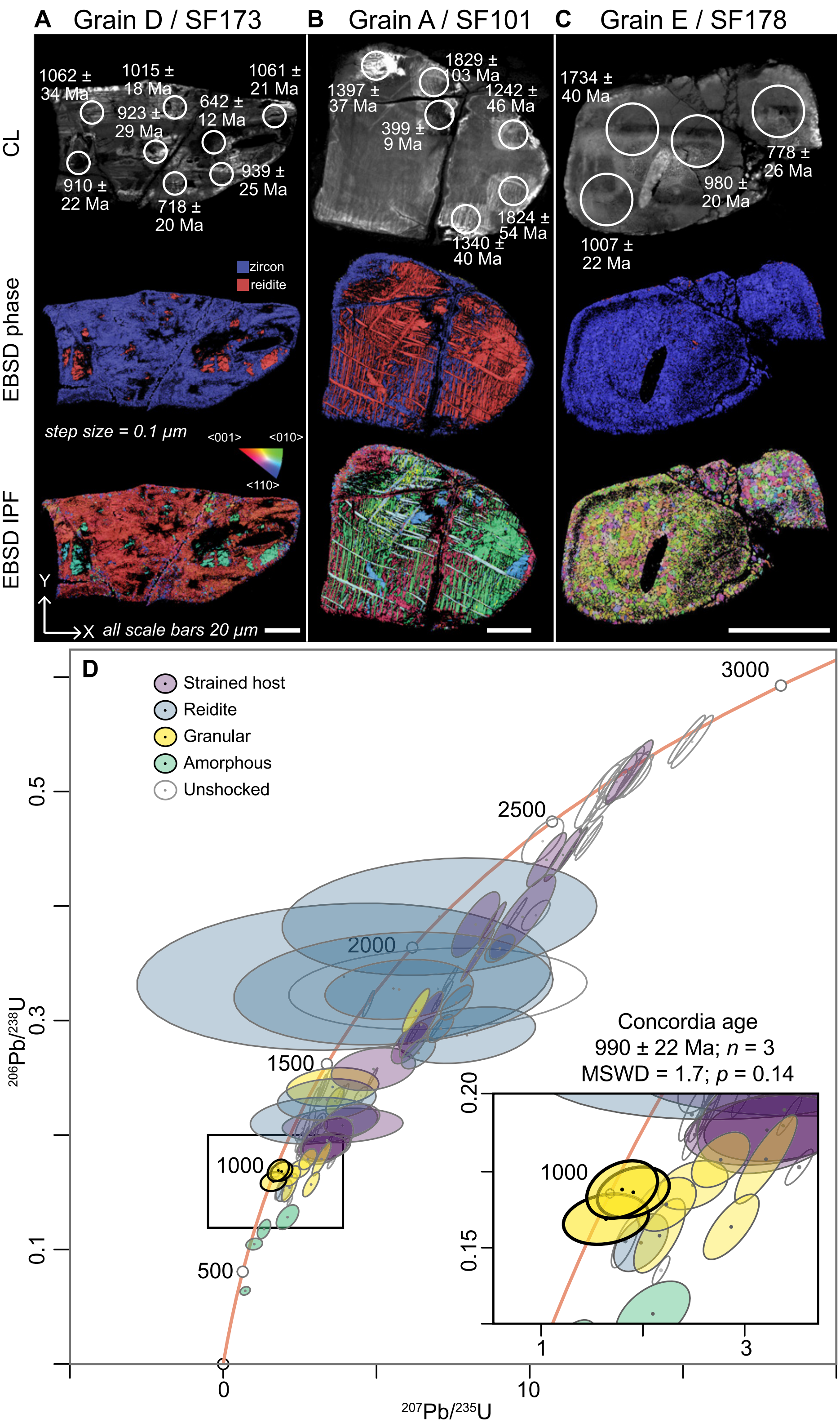

Figure 2. Cathodoluminescence (CL) and electron backscatter diffraction (EBSD) phase and inverse pole figure (IPF) maps of characteristic shocked zircon grains and concordia diagram of U-Pb analyses from the Stac Fada Member. (A) Reidite-bearing zircon with subdomains of granular recrystallization. (B) Shocked zircon grain converted to lamellar reidite. Zircon granules are limited to grain rim and along open fractures. (C) Fully shock-recrystallized (granular) zircon grain. Grain/analysis IDs are shown at the top of each panel. $^{206}Pb/^{238}U$ ages are marked on CL images. (D) Wetherill concordia diagram of U-Pb analyses collected from all Stac Fada Member zircon grains, color coded by microstructural type. Uncertainty ellipses are shown at the 2σ level.

To estimate the most likely time of radiogenic-Pb loss driven by fluid-rock interaction, we performed a concordant-discordant comparison test (Kirkland et al., 2017) of unshocked zircon from this study and from published data (Kenny et al., 2019; Lebeau et al., 2020; Rainbird et al., 2001) for rocks stratigraphically below and above the Stac Fada Member. We used a Bayesian approach that assumes that the discordant zircon population was derived from crust with an age structure similar to that of the concordant population (i.e., that both were derived from the underlying Lewisian Gneiss Complex; see the Supplemental Material). In this test, the greatest similarity between the discordant population and concordant population was computed, using the Kolmogorov-Smirnov similarity test (Kolmogorov, 1933), for all possible times of Pb loss (Fig. 3). This test yielded two key results. Firstly, the greatest similarity between concordant and discordant populations of the Stac Fada Member data is achieved with a Pb-loss event at ca. 1000–900 Ma. Secondly, the sedimentary units encasing (i.e., above and below) the Stac Fada Member lack the distinctive radiogenic-Pb loss probability at 1000–900 Ma (Fig. 3). Combined, these results imply that the Pb-loss event was a phenomenon related to the Stac Fada Member.

The general agreement between the age of the concordant granular zircon analyses of 990 ± 22 Ma and an early Tonian time for Pb loss in the Stac Fada Member together indicate an impact age that is consistent with the maximum depositional age for the Stoer Group of ca. 1100 Ma implied by detrital apatite (U-Pb ages of 1101 ± 38 and 1109 ± 40 Ma; Kenny et al., 2019). However, it is some 200 m.y. younger than a 1177 ± 5 Ma $^{40}Ar/^{39}Ar$ age reported previously for alkali feldspar rinds coating degassing vesicles (Parnell et al., 2011). At present, it is difficult to easily explain this discrepancy, but we highlight several observations. Firstly, the calcite-filled degassing vesicles within our studied samples are lined with plagioclase (oligoclase-andesine), not alkali feldspar (Fig. S1). Secondly, the only alkali feldspar we observe appears to be detrital based on petrographic observations and in situ Rb-Sr geochronology. This alkali feldspar yields Rb-Sr ages of ca. 1735 Ma and 1675 Ma, consistent with derivation from Paleoproterozoic granites within the Lewisian Gneiss Complex (Mason, 2016) (Fig. S7). Further, the fluid inclusion salinity and oxygen isotope composition of the $^{40}Ar/^{39}Ar$–dated alkali feldspar are distinct from those of the associated vesicle-filling calcite (Parnell et al., 2011), indicating that they could not have precipitated from the same fluid. The consistency of our geochronology across multiple techniques provides compelling evidence that the U-Pb date of 990 ± 22 Ma constrains the timing of the Stac Fada impact event.

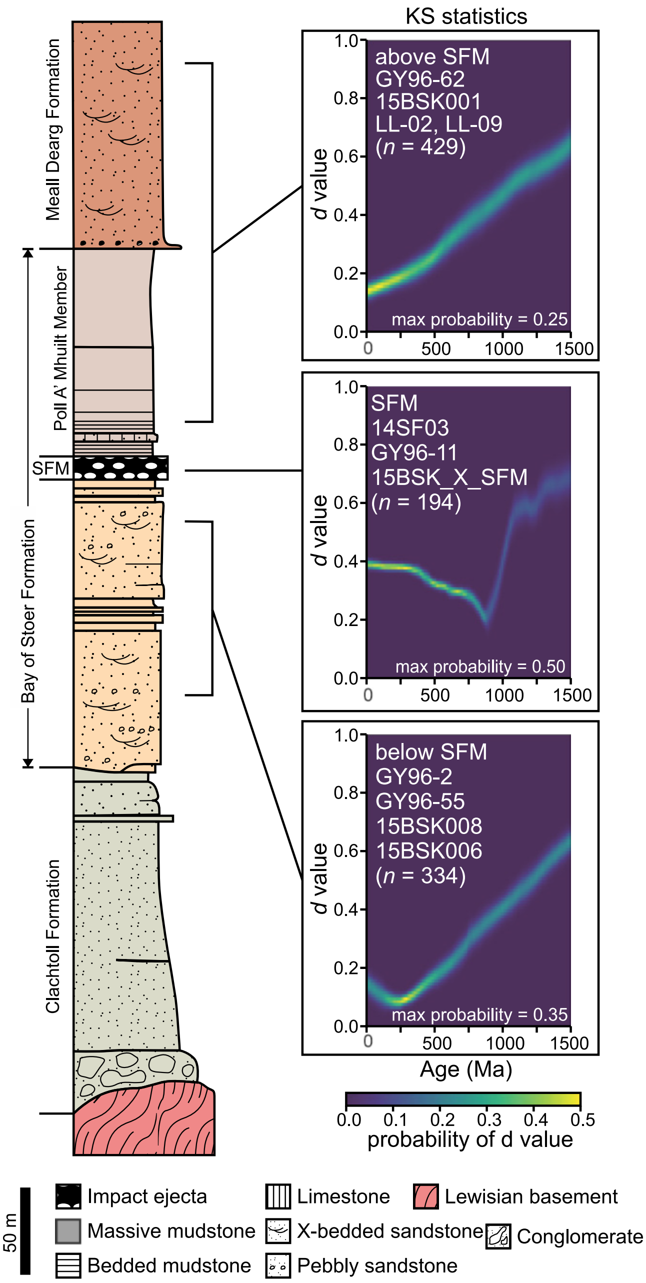

Figure 3. Stratigraphic column and Kolmogorov-Smirnoff (KS) plots of Pb-loss trends through the Stoer Group. KS plots are compiled from U-Pb data from this study and others (Kenny et al., 2019; Lebeau et al., 2020; Rainbird et al., 2001). Zircon grains from the Stac Fada Member (SFM) show dominant Pb loss (minimum *d* value) at ca. 900 Ma, whereas Pb loss below and above the Stac Fada Member is dominated by modern (Phanerozoic) Pb loss. Stratigraphic column is modified from Parnell et al. (2011). 15BSK_X_SFM from Kenny et al. (2019) is a combination of SFM samples from various localities.

IMPLICATIONS

The use of complementary chronological techniques represents an advance in our ability to temporally constrain impact events, especially ejecta deposits likely to have undergone extensive fluid-rock interaction (Osinski et al., 2021). Our 990 ± 22 Ma estimate on the timing of the impact and the depositional age of the Stac Fada Member indicates that the Stoer Group was deposited during the later stages of the Grenville orogeny and the assembly of NE Rodinia in a complex collision zone between Laurentia and Amazonia (±Baltica). The unconformably overlying Torridon Group has also been related to the same overall tectonic setting as the Stoer Group and is thought to have been deposited in a foreland basin on the north side of the Grenville orogen (Krabbendam et al., 2008). The Torridon Group has a maximum depositional age of ca. 1000 Ma based on detrital zircon (Krabbendam et al., 2017), and shales within it have yielded whole rock Rb-Sr diagenetic ages of 994 ± 48 and 977 ± 39 Ma (Turnbull et al., 1996) (Fig. 4). If these diagenetic whole rock Rb-Sr data are reliable, then deposition and lithification of the 2.5-km-thick Stoer Group, its tilting and erosion, and subsequent deposition of the 6-km-thick Torridon Group occurred during a span of 50–60 m.y. Such time scales are feasible, one example being that of the Alpine Swiss Molasse basin with its syn- through late-orogenic intrabasinal unconformities and preserved thickness (up to 5 km) that was deposited over an ~30 m.y. time interval (e.g., Burkhard and Sommaruga, 1998). If the Stoer Group was deposited in a thrust-top basin as proposed (Metcalfe et al., 2024), then the Swiss Molasse basin is an apt analogue given that it, too, is a piggyback basin, carried along in the hanging wall of the basal Jura thrust fault (Burkhard and Sommaruga, 1998).

Further implications that we highlight include the overlap between our ca. 990 Ma best estimate for the impact age and $^{40}Ar/^{39}Ar$ ages of pseudotachylyte veins (980 ± 39 Ma, 999 ± 31 Ma, and 1024 ± 30 Ma) within rocks of the Lewisian Gneiss Complex farther to the south (Sherlock et al., 2008). Although the ages of these veins have been interpreted to date Grenvillian deformation, their temporal correspondence to the age of the Stac Fada impact suggests that they may record frictional melting resulting from the impact (Spray, 2010). This age is also similar to that of recently discovered shock-metamorphosed zircon grains from glaciofluvially transported impact melt rock in Greenland (Hyde et al., 2024). Lastly, our revised age of 990 ± 22 Ma redefines the age of some of the oldest known marine to freshwater eukaryotes on Earth (Strother et al., 2011) to the early Neoproterozoic rather than late Mesoproterozoic, with profound regional stratigraphic consequences.

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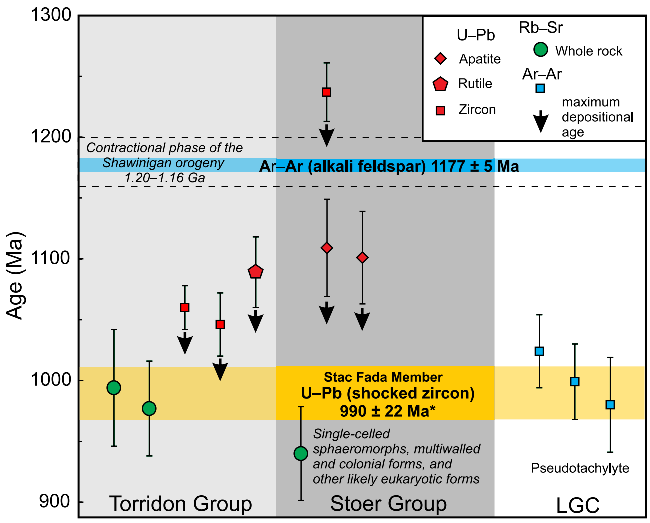

Figure 4. Geochronology of the Stoer Group in context of other constraints on stratigraphic age. LGC denotes Lewisian Gneiss Complex. Blue band shows age of Stac Fada impact from Parnell et al. (2011), and yellow band shows revised age based on our U-Pb zircon analyses. Ages are from: detrital zircon (Kenny et al., 2019), rutile (Pereira et al., 2020), apatite (Kenny et al., 2019), whole rock (Moorbath, 1969; Turnbull et al., 1996), pseudotachylyte (Sherlock et al., 2008), and feldspar (Parnell et al., 2011). Microfossils in the Stoer Group are detailed in Strother et al. (2011). Maximum depositional age constraint is provided by youngest crystallization age for a detrital component. Asterisk (*) symbol denotes results from this work. Error bars are at the 2σ level.

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